

EXTRAGALACTIC H_3O^+ : SOME CONSEQUENCES

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Abstract. We discuss some implications of our recent detection of extragalactic H_3O^+ : the location of the gas in M82, the origin of energetic radiation in M82, and the possible feedback effects of star formation on the cosmic ray flux in galaxies.

1 Introduction

Last year saw the first detection of the H_3O^+ molecule outside the Galaxy (Van der Tak et al. 2008). Using the new 16-pixel HARP imaging spectrometer on the James Clerk Maxwell Telescope, line emission at a rest frequency of 364 GHz was detected towards the prototypical starburst galaxy M82 and the prototypical ultraluminous merger Arp 220. The derived H_3O^+ abundances and $\text{H}_3\text{O}^+/\text{H}_2\text{O}$ ratios imply very high ionization rates for the dense molecular gas in the nuclei of these two galaxies. Chemical models (Meijerink et al. 2007) indicate that the origin of this high ionization is irradiation by X-rays in the case of Arp 220, whereas for M82, a combination of ultraviolet light and cosmic rays is needed. The high ionization rates of these galactic nuclei make magnetic fields more effective in retarding their gravitational collapse and the formation of stars. The origin of the irradiation in M82 is the evolved starburst (Förster Schreiber et al. 2003), whereas for Arp 220, an AGN may be needed, as claimed before by Downes & Eckart (2007). Naturally, some questions remain, of which this paper discusses a few.

2 Location of the H_3O^+ in the nucleus of M82

The velocities and widths of the two components of the H_3O^+ line profile observed toward M82 may be used to constrain the location of the gas. Observations of CO emission lines toward the M82 nucleus show a flattened structure of size $\approx 50 \times 20''$

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(1000×400 pc) with emission peaks on its north-eastern and south-western ends. The velocity field is well described by a monotonic gradient along the major axis, so that the structure is probably a rotating ring or torus. Observations of CO 6–5 with the JCMT (Seaquist et al. 2006) show a third peak in the middle, which is even better visible in interferometric images of CO 1–0 (Walter et al. 2002) and known as the ‘central hotspot’.

The simple velocity structure of the rotating ring implies that the velocities of the H_3O^+ components correspond to unique positions. In particular, the velocity of the narrow component of $V_{\text{helio}} \approx 270 \text{ km s}^{-1}$ corresponds to the inner edge of the north-eastern peak, which is just covered by the beam of the H_3O^+ observations. The width of the narrow component agrees with that of the CO emission from the north-eastern peak.

The velocity of the broad H_3O^+ component of $V_{\text{helio}} \approx 220 \text{ km s}^{-1}$ corresponds to a position right between the two main CO peaks. Since the width of this component is much larger than the systematic velocity gradient within one JCMT beam, the most plausible origin of the broad component is the ‘central hotspot’ of molecular emission. This hotspot is located close to the dynamical center of M82 and shows large line widths in several other molecular lines. The distribution of H_3O^+ in M82 thus appears to mimic that of other dense gas tracers such as HCN (Mauersberger & Henkel 1991).

3 Origins of energetic radiation in M82

The X-ray luminosity (L_X) of M82 on arcminute scales as measured by ROSAT and ASCA is $\sim 2 \times 10^{41} \text{ erg/s}$ after correction for internal absorption (Moran & Lehnert 1997). In the central $< \sim 100 \text{ i,pc}$ of M82, where H_3O^+ has been detected, both the nuclear non-thermal component and the central thermal component may contribute to the ionization of the molecular gas; the superwind is too far away and its luminosity too low for it to play a role. Observations with *Chandra* and XMM-*Newton* (Zezas 2006) seem to indicate that the emission in the extended nuclear region is dominated by high-mass X-ray binaries (HMXBs) and so-called ultra-luminous X-ray sources (ULXs). The X-ray emission from a starburst is dominated by HMXBs, such that L_X may be used to estimate its star formation rate (Grimm et al. 2003). Future spatially and spectrally resolved observations of H_2O line emission in M82 may be used to determine the $\text{H}_3\text{O}^+/\text{H}_2\text{O}$ ratio for both components of H_3O^+ emission and to characterize the ionization state of the molecular gas in M82 as a function of position in the nuclear disk.

4 Effects of star formation on the cosmic-ray flux

The main astrophysical interest in H_3O^+ is the use of the $\text{H}_3\text{O}^+/\text{H}_2\text{O}$ abundance ratio as a probe of the ionization rate of dense molecular gas. This rate is an important parameter for the ability to form stars, because it determines whether magnetic fields may be effective in supporting the cloud against gravitational collapse. The ionization rate of dense molecular clouds is dominated by ultraviolet

light and X-rays near their surfaces, and low-energy cosmic rays ($E \lesssim 1 \text{ GeV}$) in their interiors. Foreground absorption often hides these types of radiation from direct observation, which is why H_3O^+ observations are so useful.

Recently, Pellegrini *et al.* (2007) proposed a model for the photodissociation region M17 where the thickness of the atomic gas layer between the ionized and molecular components is determined by magnetic pressure rather than gas pressure. The motivation for this model is the unusually strong magnetic field measured in M17 through the Zeeman effect on the HI 21 cm line (Brogan *et al.* 1999). Similar results were found for the neutral gas in front of the Orion nebula (the so-called veil) by Abel *et al.* (2004). The idea is that soon after the formation of a star cluster, starlight momentum and gas pressure from the ionized region compress the surrounding neutral gas, where the magnetic pressure builds up until it can withstand the external pressure. See also Ferland (this volume).

A consequence of Pellegrini's model would be that the cosmic-ray flux in the gas surrounding the star cluster is also enhanced, if the cosmic rays are trapped in the magnetic field. The efficiency of this trapping depends on the geometry of the magnetic field, in particular whether the field lines are open or closed. Direct tests of this model are not easy because the Zeeman effect is difficult to measure. However, an indirect test would be to look for correlations between the cosmic-ray ionization rates of star-forming regions with their stellar luminosity.

Figure 1 shows recent observational estimates of the cosmic-ray ionization rate in dense molecular clouds plotted against their luminosity. Although the estimates are probably only accurate to order of magnitude, a trend does appear to be visible. The possible correlation cannot just be a distance effect because the ionization rates are local quantities derived from the ratio of two molecular abundances. Thus, star formation may indeed influence the local cosmic-ray flux.

Besides variations with luminosity, the cosmic-ray ionization rate is also known to differ between diffuse and dense clouds. Ionization rates in diffuse gas are factors of 3–10 higher than those in dense clouds in the same region which are exposed to the same incident cosmic-ray flux. This effect is shown by the open symbols in Figure 1, with data from Le Petit *et al.* (2004) for ζ Per, McCall *et al.* (2002) for Cyg OB2, Oka *et al.* (2005) for Sgr A and Geballe *et al.* (2006) for IRAS 08572. The offset between the diffuse and the dense clouds must be due to propagation effects, and scattering of cosmic rays off plasma waves may play a role (Padoan & Scalo 2005), but only at low column densities ($A_V \lesssim 10$). In the bulk of the clouds, the lifetime τ of the cosmic rays is probably limited by energy losses, which scale as $\tau \sim 2 \times 10^5 (n_H/300 \text{ cm}^{-3})^{-1} \text{ yr}$ (Gabici *et al.* 2007).

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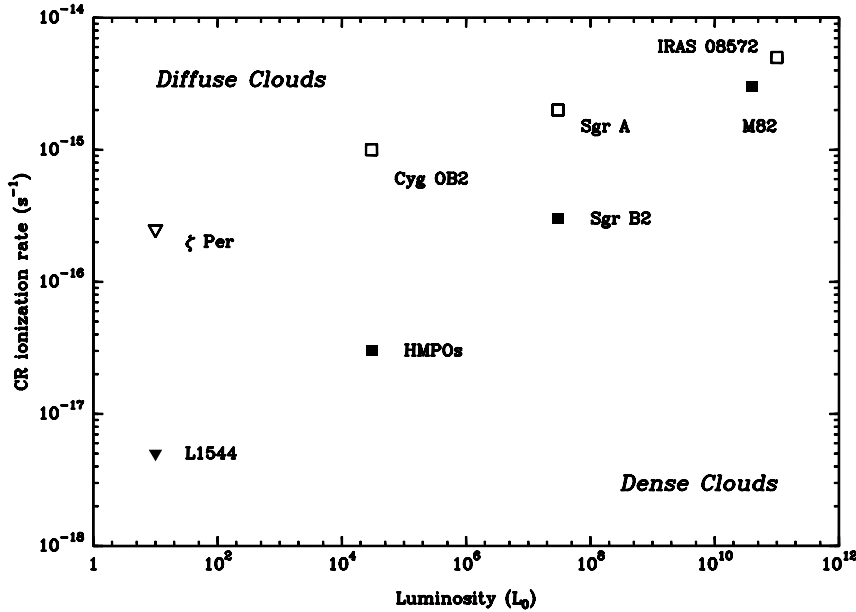


Fig. 1. Relation between cosmic-ray ionization rate and bolometric luminosity. Ionization rates are from Caselli et al. (2002), Van der Tak & van Dishoeck (2000), Van der Tak et al. (2006) and Van der Tak et al. (2008); luminosities are from Van der Tak et al. (2000), Lis & Carlstrom (1994) and Spaans & Meijerink (2007). The luminosity of the pre-stellar core L1544 is an upper limit.

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